A bright off-nuclear X-ray source: a type IIn supernova, a bright ULX or a recoiling super-massive black hole in CXO J122518.6+144545

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ABSTRACT

In this Paper we report the discovery of CXO J122518.6+144545; a peculiar X-ray source with a position $3.6\pm0.2''$ off-nuclear from an SDSS DR7 z=0.0447 galaxy. The $3.6''$ offset corresponds to 3.2 kpc at the distance of the galaxy. The 0.3–8 keV X-ray flux of this source is 5×10^{-14} erg cm^{-2} s^{-1} and its 0.3–8 keV luminosity is 2.2×10^{41} erg s^{-1} (2.7×10^{41} erg s^{-1}; 0.5–10 keV) assuming the source belongs to the associated galaxy. We find a candidate optical counterpart in archival HST/ACS g′– band observations of the field containing the galaxy obtained on June 16, 2003. The observed magnitude of g′ = 26.4±0.1 corresponds to an absolute magnitude of −10.1. We discuss the possible nature of the X-ray source and its associated candidate optical counterpart and conclude that the source is either a very blue type IIn supernova, a ULX with a very bright optical counterpart or a recoiling super-massive black hole.

Key words: galaxies:individual: SDSS J122518.86+144547.7 — binaries — X-rays: binaries — X-rays:individual:CXO J122518.6+144545

1 INTRODUCTION

Off-nuclear ultra–luminous X–ray sources (ULXs) have been found in different galaxies. It has been found that many of the ULXs are associated with active star–forming regions (e.g. in the Antennae, Fabbiano et al. 2003), optical emission line nebulae (e.g. Pakull et al. 2006) and radio halos (e.g. Miller et al. 2005; Lang et al. 2007).

In addition, six off-nuclear sources with $L_x \gtrsim 10^{41}$erg s^{-1} have been found (i.e. in the Cartwheel galaxy, Wolter et al. 2006; M 82 X-1, Feng & Kaaret 2009 and Strohmayer & Mushotzky 2003; in NGC 2276, Davis & Mushotzky 2004; ESO 243-49, Farrell et al. 2009; in NGC 5775, Li et al. 2008 and M101 ULX-1, Kong et al. 2004a). They are called hyper-luminous X-ray sources. The optical counterpart has been found and studied in only a sub-sample of these (M101 ULX-1, Kong et al. 2004b, Liu 2009; ESO 243-49, Soria et al. 2009; and possibly M 82 X-1, Kaaret et al. 2004).

An important question in the work on the ULXs is whether the emission is isotropic or not. If beaming is significant (King et al. 2001) an intermediate–mass black hole

(IMBH) or super-massive black hole (SMBH) is not needed to explain sources with luminosities up to $\approx 10^{40}$erg s^{-1}. For several sources, ionizing luminosities derived from the optical emission lines and the resolved radio bubbles indicate that beaming is not important (Pakull & Mirioni 2003; Miller et al. 2005; Lang et al. 2007) and hence these sources are good candidates for IMBHs. For the sample of hyper-luminous ULXs, their X-ray luminosity seems too high for a stellar mass black hole even in the presence of some beaming. For their classification there are currently three possible scenarios: very bright type IIn supernovae, IMBHs and recoiling SMBHs. We will briefly introduce these options.

The X-ray brightest supernovae are of type IIn (Immler & Lewin 2003). Therefore, in principle, they could be responsible for a sub-sample of the very bright ULXs. Time variability in the X-ray as well as in the optical band can be used to constrain this possibility.

In the cold dark matter (ΛCDM) cosmological scenario current (z=0) galaxies are the product of hierarchical mergers of smaller galaxies. These smaller building blocks also host black holes in their centers (Kormendy & Richstone

1995). Evidence for this comes from the observed M–σ relation (Magorrian et al. 1998; Ferrarese & Merritt 2000). Furthermore, several so called dual Active Galactic Nuclei (AGNs) have been found (cf. Comerford et al. 2009 and references therein). After a galaxy merger, the two black holes will eventually merge as well (see Begelman et al. 1980).

Recent fully relativistic numerical simulations allow for the calculation of the linear angular momentum that is transported by gravitational wave radiation during the final plunge in the black hole – black hole merger (Pretorius 2005). The transport of linear angular momentum acts as a kick on the newly formed black hole merger product: gravitational wave recoil. This effect had been estimated before by for instance Bekenstein (1973) and Redmount & Rees (1989). When a black hole merger takes place in the presence of an accretion disc, the recoiling black hole will take along the part of the nuclear star cluster and accretion disc that falls within its gravitational influence area ($R_{\rm infl} \approx 0.3 M_8/v_{1000}^2$ pc; where M_8 is the mass in units of $10^8 {\rm M}_\odot$ and v_{1000} is the velocity in units of 1000 km s^{-1}; Bonning, Shields & Salviander 2007). Binary SMBHs surrounded by an accretion disc will have emptied the inner portion leaving a gap in the disc. Upon a kick this gap will refill on a short timescale (Loeb 2007) and AGN activity will resume. Subsequently, such recoiling black holes may become visible as off–nuclear AGNs (Bonning et al. 2007; Volonteri & Madau 2008; Fujita 2009). The disc mass will allow for the AGN activity to last tens of millions of years (cf. Bonning et al. 2007).

The source SDSS J092712.65+294344.0 has been proposed as a recoiling massive black hole (Komossa et al. 2008). However, different interpretations as a binary black hole (Bogdanović et al. 2009; Dotti et al. 2009) or a chance alignment with a more distant source in the same cluster have also been proposed (Shields et al. 2009a). Similarly, SDSS J105041.35+345631.3 and SDSS J153636.22+044127.0 have been suggested as recoiling SMBH candidates (Shields et al. 2009b; Boroson & Lauer 2009, respectively). The main difference between the IMBH and the SMBH scenario for the hyper-luminous sources lies in their optical properties. The recoiling SMBHs should carry with it the broad line region. Therefore, they should contain broad lines in their optical spectra whereas this is not the case for the IMBH scenario.

In this Manuscript we discuss the nature of another hyper-luminous off-nuclear X-ray source: CXO J122518.6+144545.

2   OBSERVATIONS, ANALYSIS AND RESULTS

2.1   *Chandra* **X-ray observation**

In order to search for bright off-nuclear X-ray sources, we have selected galaxies from the Sloan Digital Sky Survey (SDSS) data release (DR) number 7. We have cross-correlated this database with the *Chandra* source catalog in order to search for X-ray active sources. Out of the resulting matches we have selected those for which the *Chandra* detection does not coincide with the position of the galaxy center. We selected sources where the distance between the center of the galaxy as determined by the SDSS-DR7 and the
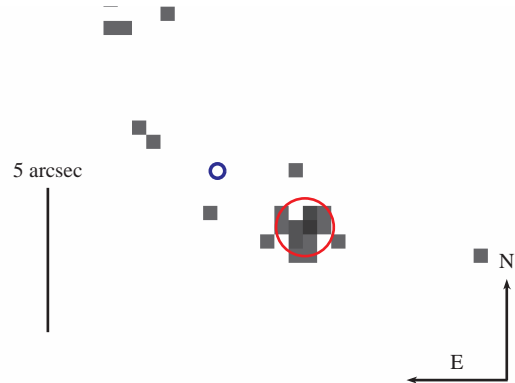

Figure 1. Zoom in around the *Chandra* ACIS-S3 position of the off-nuclear source (indicated with the red (larger) circle with a radius of 1″). The blue (smaller, thick line) circle indicates the SDSS DR7 position of the centre of the galaxy, its radius is 0.25″.

X-ray position is less than 10″ but larger than 2″. Furthermore, the error on the X-ray position had to be less than 2″. Next, we determined the redshift of the galaxy (photometric or spectroscopic) from the SDSS database and we kept sources with a luminosity larger than 1×10^{40} erg s^{-1} using the flux measured in the *Chandra* source catalog. Finally, we have plotted the X-ray position on the SDSS r'-band image to visually verify the resulting sources. Below, we report on the X-ray source CXO J122518.6+144545.

This source has a position 3.6″ off-nuclear from a galaxy identified in the SDSS DR7 as having a redshift z=0.0447 (see Fig. 1 and 2). The SDSS DR7 measured centre of this galaxy is at Right Ascencion (R.A.; J2000)=12:25:18.860 (186.328583 in decimal degrees) and the Declination (Dec; J2000)=14:45:47.704 (14.763251 in decimal degrees). We have retrieved the X-ray observation with observation ID 8055 from the *Chandra* archive and reprocessed the events with calibrations available in CALDB version 4.1.3 using the version 4.1.2 of the *Chandra* X-ray center CIAO tools. The exposure time for the observation with ID 8055 is 5093 s. The source is detected 1.7′ off-axis on the ACIS S3 CCD.

Using WAVDETECT we detect another source 84.3″ away from CXO J122518.6+144545. This source is the brightest detected X-ray source and it can be identified with a bright point source in the SDSS g'- and r'-band images (g'=20.10±0.02 and r'=19.25±0.01). We use its accurate SDSS DR7 r'-band position of R.A.=12:25:19.451 (186.33104668) and Dec=14:47:09.262 (14.78590606) to determine a boresight correction for the *Chandra* observation. The optical positional accuracy depends on the localization uncertainty which for stars with $r' < 20$ is negligible (Pier et al. 2003) and on the statistical and systematic uncertainty in tying the SDSS r'-band field to the ICRS reference frame. We use the conservative values provided by Pier et al. (2003) (see Table 1).

Using this accurate r'-band position, we determine a bore-sight correction of dRA:0.03±0.08″ and dDEC:-0.23±0.08″. The error of 0.08″ on each coordinate stems from the uncertainty in localizing the X-ray bore-sight correction source. After applying this bore-sight correction using the tool WCS_UPDATE we ob-
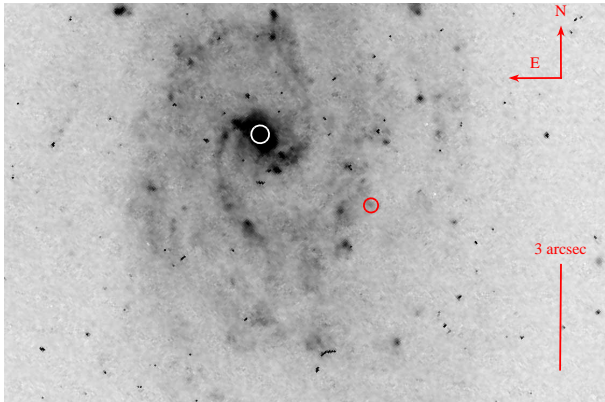
Figure 2. HST/ACS g'–band image with an exposure time of 750 s revealing the (cluster of) stars in the *Chandra* error circle. The grey circle (red in the colour version, South-West of the image centre) is at the *Chandra* position and the radius of $0.2''$ is equal to the overall astrometric error in the position of the X-ray source. The white circle indicates the SDSS DR7 position of the centre of the galaxy, the radius is $0.25''$. The figure is made from the combined, 750 s-long drizzled HST image.

Table 1. Sources of uncertainty used for the astrometry.

Source	Uncertainty
Uncertainty tying SDSS frame to ICRS	30 milli-arcsec**
Uncertainty tying SDSS frame to ICRS	60 milli-arcsec*
X-ray localization uncertainty CXO source	0.15 arcsec*
Remaining X-ray bore sight uncertainty	0.12 arcsec*

* statistical uncertainty.
** systematic uncertainty.

tain a best fit position for the off-nuclear X-ray source CXO J122518.6+144545 of R.A.=12:25:18.650(9) [186.32771(3) degrees] and Dec=14:45:45.76(8) [14.76271(2) degrees] using WAVDETECT where the number in-between brackets denotes the 68 per cent confidence uncertainty in the last digit. These errors are due to the error in the source localization on the CCD alone.

The final uncertainty on the position of the off-nuclear X-ray source is the quadratic sum of the centroiding uncertainty of the X-ray source, the uncertainty in the X-ray bore-sight correction and the uncertainty in the astrometry of the r'-band image (see Table 1). The overall astrometric uncertainty on the X-ray source position is $0.19''$ which we round-off to $0.2''$.

Due to larger centroiding uncertainties in the positions of fainter X-ray sources the association of such fainter sources with a candidate optical counterpart is less certain. Therefore, we prefer to use the bore-sight correction determined using only the one bright X-ray source mentioned above. This does imply that we ignore any uncertainty in the roll angle of the satellite, which could introduce a small effect in the bore-sight correction. Since we also improve the astrometry HST images using the SDSS r'-band (see below) we could use astrometry relative to the SDSS r', however, the contribution of linking the SDSS r' frame to the ICRS as-

trometric standard frame to the error budget is small, hence we prefer to use the absolute astrometric solution.

We have selected a circular region of 6 pixel ($\approx 3''$) radius centered on the source position to extract the source counts in the energy range of 0.3–8 keV. We limited the radius to exclude the centre of the galaxy. Similarly, we have used a circular region with a radius of 80 pixels away from any source but on the same S3 CCD to extract background counts. We have made redistribution and auxilliary response matrices for the source and background region separately.

The net number of background subtracted source counts is 22. The predicted number of background source photons is 4–5. Standard Poisson statistics shows that this is a very significant detection with a chance of less than 1×10^{-8} to be due to a fluctuation in the background. Using XSPEC version 11.3.2p (Arnaud 1996) we have fitted the spectrum of CXO J122518.6+144545 using Cash statistics (Cash 1979) modified to account for the subtraction of background counts, the so called W-statistics[1]. We have used an absorbed power-law model (PEGPWRLW) to describe the data.

Due to the relatively low number of counts we fix the interstellar extinction during the fit to 2.8×10^{20} cm^{-2}; the Galactic foreground N_H in the direction of the source found by Dickey & Lockman (1990). The power-law index and normalisation were allowed to float. The errors on the parameters are substantial due to the low number of counts; we obtain a power-law index of 0.9 ± 0.3 and an unabsorbed flux of $(5.4 \pm 1.6) \times 10^{-14}$ erg cm^{-2} s^{-1} in the range 0.3–8 keV. The errors are at the 68 per cent confidence level. If we fix the power-law index to 1.9, such as found often for AGN, the extinction is $(5 \pm 2) \times 10^{21}$ cm^{-2} implying a significant amount of extinction above the Galactic extinction in the direction of the source.

Using standard cosmology the redshift converts to a distance of 182.6 Mpc, which makes the X-ray luminosity in the range 0.3–8 keV $L_X = 2.2 \times 10^{41}$ erg s^{-1}, for comparison the 0.5–10 keV luminosity is $L_X = 2.7 \times 10^{41}$ erg s^{-1}. We searched for variability in the rate of arrival of the photons but we found none. Despite the appearance of two flare-like features in the lightcurve, a Kolmogorov–Smirnov (Press et al. 1992) test showed that the probability that the data are consistent with the null-hypothesis of a constant photon arrival rate is 61 per cent.

2.2 *HST* ACS observations

We have analysed archival Hubble Space Telescope (HST) data obtained with the Advanced Camera for Surveys (ACS) on June 16, 2003 (MJD 52806), program GO-9401 and with the Wide Field Planetary Camera 2 (WFPC2) on February 15, 2008 (MJD 54511), program GO 11083. The ACS/WFC HST observations consist of 2×560 s and 1×90 s exposures in the F850LP (SDSS z'-band) filter and 2×375 s exposures in the F475W (SDSS g'-band) filter. The WFPC2 observations consist of 3×700 s exposures in the F300W filter ($\lambda = 2919.8$Å; $\Delta\lambda = 740.2$Å).

The photometry of the ACS images was performed using the ACS module in the software package DOLPHOT

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[1] see http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/

(version 1.1)[2]. Following the DOLPHOT/ACS User's Guide, the images were processed by masking all bad pixels using the ACSMASK task and the multi-extension FITS files were split into single chip images using the SPLITGROUPS task before performing photometry. Finally the sky background for each chip was calculated with the CALCSKY task. We run DOLPHOT on both bias and flat-field corrected `flt` images and on cosmic ray cleaned and flat-field corrected (`clr`) archival images. We tested different sets of parameters for the photometric measurements. These tests include the setting recommended in the DOLPHOT/ACS User's Guide and the settings described in Dalcanton et al. (2009). The different parameter sets provide results in agreement within the photometric errors. We report here the measurements derived using the parameter set recommended in the DOLPHOT/ACS User's Guide.

For the photometric analysis we exclude the measurements obtained on one of the 375 s g'-band images due to the presence of charge due to a cosmic ray hit near the *Chandra* position. We improved the absolute astrometric accuracy of the remaining ACS frame using 5 point sources that are detected in the SDSS-DR7 r'-band image. The resultant error on the astrometry of the ACS `drz` frame is dominated by the astrometric accuracy of the SDSS r' band which is better than 0.1″ (Pier et al. 2003). We detect a point source inside the *Chandra* error circle in the remaining 375 s image (see Fig. 3) with coordinates R.A. (J2000)=12:25:18.65, Dec. (J2000)=+14:45:45.8 (R.A.=186.327708, Dec.=14.762722 in decimal degrees) and g' magnitude of 26.4 ± 0.1 mag in the VEGA magnitude system. The object is classified as stellar and is well recovered by the DOLPHOT photometric package. There is no detection of this source in the z'-band images (or any other source within the *Chandra* error circle). Following Crockett et al. (2009) we estimate a 3-σ upper limit magnitude at the position of the source of $z' > 25.7$. This yields $g' - z' \lesssim 0.7$ for the optical counterpart.

The source is not detected in the *Chandra* error circle in the WFPC2 F300W images either. We followed Crockett et al. (2009) using the latest charge transfer inefficiency corrections parameterized by Dolphin (2009) to calculate a 3-σ upper limit magnitude of > 22.56 in the VEGA magnitude system.

3   DISCUSSION

We have located a peculiar X-ray source with a position 3.6″ off-nuclear from an SDSS DR7 z=0.0447 galaxy (see Fig. 1 and 2). The 3.6″ corresponds to 3.2 kpc at the distance of the galaxy. The presence of another X-ray source in the same observation coinciding with a bright optical point source, allows us to register the *Chandra* observation, reducing the astrometric uncertainty in the position of the off-nuclear AGN-candidate to less than 0.2″, making the 3.6″ offset highly significant. The 0.3–8 keV X-ray flux of this source is 5.4×10^{-14} erg cm^{-2} s^{-1} and its 0.3–8 keV (0.5–10 keV) luminosity is 2.2×10^{41} erg s^{-1} (2.7×10^{41} erg s^{-1}) given the redshift of the galaxy (z=0.0447, d=182.6 Mpc). We find a candidate optical counterpart in archival
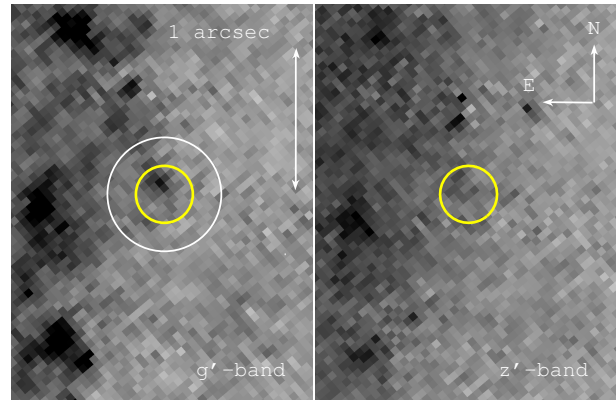
Figure 3. Zoom-in of the HST/ACS g'-band (*left panel*) and z'-band (*right panel*) image revealing the (cluster of) stars in the *Chandra* error circle present in the g'-band whereas this source is not clearly detectable in the z'-band. The white, smaller circle (yellow in the colour version) is at the *Chandra* position and the radius of 0.2″ is equal to the overall astrometric error in the position of the X-ray source. The larger, white, circle in the g'-band image represents the 90 per cent confidence region of the position of CXO J122518.6+144545. The figure is made from a single drizzled g'-band and the combined drizzled z'-band images.

HST/ACS g'–band observations of the field containing the galaxy obtained on June 16, 2003. The observed magnitude of $g' = 26.4 \pm 0.1$ corresponds to an absolute magnitude of -10.1 taking a foreground extinction from our Galaxy of $A_{g'} = 0.18$ magnitudes into account. These findings make this source an unusually bright ULX, a very bright supernova, a recoiling black hole or a background AGN (with higher luminosity). We discuss these possibilities below.

If this X-ray source is due to a supernova, the 0.5–10 keV X-ray luminosity is among the highest measured for supernovae. The X-ray brightest supernovae are of type IIn, this implies that the maximum optical g'-band magnitude was ≈ 17.3 (with mean absolute blue magnitude of -19.15 type IIn are also optically among the brightest supernovae; Richardson et al. 2002). Now, more than 6 years after the initial HST/ACS observations, the source magnitude will have changed considerably. The exact way and amount are difficult to predict as many scenarios are possible since the optical lightcurves of type IIn supernovae are heterogeneous and we do not know the explosion date. The supernova could have exploded in between the serendipitous HST/ACS and the X-ray observation or before the HST/ACS observation. The X-ray luminosity of the X-ray bright type IIn supernovae peaks around 400-1000 days after the explosion making it impossible to discriminate between the different scenarios on the basis of the single epoch X-ray and optical observations. The $g' - z' \lesssim 0.7$ colour of the optical counterpart candidate is blue for a type IIn supernova origin of the counterpart (cf. Tsvetkov 2008 for typical type IIn colours). If the supernova occurred in between the HST/ACS and the *Chandra* observation the HST/ACS images are of the supernova progenitor star (cluster). The SDSS imaging data of this galaxy was taken a few weeks before the HST data and thus cannot help us deciding between these scenarios.

In the ULX case the majority of known optical counterparts have blue colours and they are often embedded in an ionized optical nebula (Grisé et al. 2008 and references

therein). In addition, the counterparts are usually part of small young star clusters or OB associations (e.g. Zezas & Fabbiano 2002). The FWHM of the ACS image at the distance of the galaxy corresponds to more than 100 pc hence star clusters would appear as unresolved point sources. The ULX counterparts currently known would be below the detection threshold of the HST/ACS images as their absolute optical magnitude M_V is between -4 and -9 (cf. Roberts et al. 2008) while the source present in the HST/ACS observation has an absolute g' magnitude of -10.1.

This absolute magnitude is similar to the absolute magnitude of the counterpart of ESO 243-49 proposed by Soria et al. (2009). The blue colours of the candidate counterpart to CXO J122518.6+144545 make it hard to reconcile CXO J122518.6+144545 with the scenario of an IMBH in a Globular Cluster (cf. the colours of Globular Clusters in Harris 1996). Comparing the limit on the $g' - z' < 0.7$ colour with that calculated using the Padua evolution tracks (Marigo et al. 2008; Girardi et al. 2008) we find that the blue colour is consistent with an IMBH in a young, massive, star cluster.

In the recoiling black hole case the optical counterpart is probably related to the accretion disc, broad line region and the nuclear cluster that are retained. The absolute magnitude of the nuclear region in AGNs varies by more than one order of magnitude, but the faintest absolute magnitudes are $M_B = -9.8$ (NGC 4395; Filippenko & Sargent 1989) and -11.6 for NGC 3031/M81 reported by Ho et al. (1997) in line with our finding. At an off-nuclear distance of 3.2 kpc, a recoil velocity of $\sim$300 km s^{-1} is implied if the lifetime of the AGN activity is limited to $\sim 10^7$ years. The hard X-ray spectral power-law index of 0.9 ± 0.3 that we find implies that there is additional extinction beyond the Galactic value if the intrinsic source spectrum is compatible with that of an AGN.

One has to worry about chance alignments on the sky. At an 0.5–10 keV flux of 5.4×10^{-14} erg cm^{-2} s^{-1} the chance to find a background AGN in a circle with radius of $3.6''$ is very small. From the 0.5–10 keV logN – logS relation found by Mateos et al. (2008) there are approximately 76 AGN per square degree. Using this we derive that in a circle with radius of $3.6''$ on average 2×10^{-4} AGN is found. However, we searched 17 X-ray sources in galaxies with fluxes equal to or above 5×10^{-14}erg cm^{-2} s^{-1}, so considering this number of trials, leads to a probability of 4×10^{-3} that the source is a background AGN.

The X-ray spectrum of the source argues against a background AGN. The hard X-ray spectrum of the source together with an 0.5-2 keV flux of $9 \pm 3 \times 10^{-15}$erg cm^{-2} s^{-1} make that the source falls well below the trend between power-law index and source 0.5-2 keV flux found by Mateos et al. (2005) in their study of the Lockman Hole IV (see their figure 4). The X-ray to optical flux ratio in the g'-band is 87 and in the z'-band this is larger than 84, whereas most *Chandra* selected AGNs have values in the R-band below 10 (e.g. Barger et al. 2003; Laird et al. 2009). If the optical counterpart is unrelated to the X-ray source the X-ray to optical flux ratio is larger still. However, if there is additional absorption local to the AGN, the X-ray to optical flux ratio has been observed to be larger than 90 (Civano et al. 2005), although there are very few if any of these sources known at the X-ray flux level of CXO J122518.6+144545 (cf. Ma-

teos et al. 2005). If the optical source is related to the X-ray source but due to a background AGN shining through the disc of the foreground galaxy that adds a column of 5×10^{21}cm^{-2}, the $g' - z'$ colour limit would become < -1.3 which is uncharacteristically blue for an AGN (cf. the $g' - z'$ colours of ROSAT - SDSS AGN presented in Anderson et al. 2007 have a mean $g' - z'$ colour of $\approx 0.7 \pm 0.5$).

We conclude that CXO J122518.6+144545 is a strong candidate for a recoiling SMBH, a bright ULX with a bright optical counterpart or a very blue type IIn supernova.

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